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INVESTIGATION OF PROPRIETARY AIR-ENTRAINING ADMIXTURES TO PRODUCE FROST-RESISTANT CONCRETE WITH LOW AIR CONTENT

by

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13. ABSTRACT *(Maximum 200 words)*

This report covers a laboratory investigation of six air-entraining admixtures (AEA) to determine whether adequate frost resistance could be achieved in concrete with a water-cement ratio not exceeding 0.50 and air content less than the minimum value currently recommended by the American Concrete Institute. Concrete mixtures were proportioned and tested for resistance to freezing and thawing according to the provisions of American Society for Testing and Materials (ASTM) C 266, Procedure A as required by ASTM C 233. Durability factors were determined according to the provisions of ASTM C 666. Values for spacing factors and specific surfaces of the air-void systems were measured according to the provisions of ASTM C 457.

When different AEA's were tested, the results indicated a significant difference in the frost resistance of concretes having the same air content. The AEA's with high air content provided adequate frost resistance; one AEA with medium air content provided adequate frost resistance; and none of

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the AEA's with low air content provided adequate frost resistance. The superior performance of one of the AEA's apparently resulted from smaller spacing factors and higher specific surfaces with lower air content than were present in other AEA's. At an equivalent air content, this AEA generated an air-void system comprised of smaller voids that were necessarily spaced closer together.

PREFACE

This report was prepared at the Structures Laboratory (SL) of the US Army Engineer Waterways Experiment Station (WES) under the sponsorship of the Headquarters, US Army Corps of Engineers (HQUSACE), as a part of Civil Works Investigation Studies Work Unit 31138, "New Technologies for Testing and Evaluating Concrete."

The study was conducted under the general supervision of Messrs. Bryant Mather, Chief, SL, and James T. Ballard, Assistant Chief, SL. Direct supervision was provided by Messrs. Kenneth L. Saucier, Chief, Concrete Technology Division (CTD) and Steven A. Ragan, Chief, Engineering Mechanics Branch (EMB), CTD, who was the Principal Investigator. Mr. Billy D. Neeley, EMB, directed the laboratory work. Messrs. Neeley, W. E. McDonald, and Michael K. Lloyd, EMB, prepared this report. The authors acknowledge the assistance of Messrs. Sam Wong, Percy Collins, Tom Lee, Julies Mason, Mses. Linda Mayfield and Judy Tom, CTD, during the laboratory work and preparation of this report.

Dr. Robert W. Whalin was Director of WES. COL Leonard G. Hassell, EN, was Commander and Deputy Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees*
inches	25.4	millimetres
pounds (force) per square inch	0.006894757	megapascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	0.5932764	kilograms per cubic metre
square inches per cubic inch	0.039370079	square millimetres per cubic millimetre

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$.

INVESTIGATION OF PROPRIETARY AIR-ENTRAINING ADMIXTURES TO PRODUCE FROST-RESISTANT CONCRETE WITH LOW AIR CONTENT

PART I: INTRODUCTION

Background

1. Frost damage to critically water-saturated concrete is caused by internal pressures exerted when water in pores in the paste or aggregate freezes and expands 9 percent, assuming adequate maturity (≈3,500 psi (24.1 MPa)). If the capillary pores in the paste are filled in excess of 91 percent of their volume, upon freezing the excess water must be expelled or the pores will dilate. To prevent frost damage, the freezing water must escape from a critically filled pore to a nearby air void prior to inducing damaging effects from expansion. The flow path distance between voids is therefore an important factor in the resistance of concrete to frost damage. The shorter the flow path distance from a water-filled pore to a void, the more likely it is that the expelled water will reach an accommodating air void and relieve the pressure.

2. A proper air-void system will provide protection against frost damage to the paste portion of the concrete. Klieger (1956) found that a volume of air voids equal to 9 percent of the volume of the mortar provided adequate protection. Equally important is the distribution of the air voids throughout the paste. A spacing factor, which is the average maximum distance from any point in the paste to an air void, not exceeding 0.008 in. (0.2 mm),* has provided adequate frost protection.

3. The size of air voids depends largely upon the type of air-entraining admixture (AEA) used and is expressed in terms of specific surface (square inch/cubic inch or square millimetre/cubic millimetre). The specific surface of voids in properly air-entrained concrete is typically in the range of 400 to 600 sq in./cu in. (16 to 24 sq mm/cu mm) but can be higher. The specific surface tends to increase with an increase in cement content for a

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

given air content (Powers 1954). Also, at a given air content, a higher specific surface should result in a smaller spacing factor (Mindess and Young 1981). Therefore, if a particular AEA produced smaller stable bubbles, it could be possible to have the necessary spacing factor at a lower total air content.

4. In 1984, Professor Helmuth Geymayer of Graz, Austria, and Mr. Laurence H. McCurrich, Technical Marketing Director, Fosroc Technology Ltd., Birmingham, England, related to Ms. Katharine Mather, US Army Engineer Waterways Experiment Station (USAEWES), Structures Laboratory (SL), that AEA's in use in Europe would produce air-void systems with acceptable spacing factors (0.008 in. (0.2 mm) or less) for frost protection in concrete with an air content as low as 3 percent (Mather 1984). However, Sommer (1987) reports that there can be considerable difference in the performance of these AEA's. He examined the approval tests for 13 AEA's marketed in Austria and found the resulting spacing factors fell into two groups. The better AEA's produced spacing factors from 0.005 to 0.006 in. (0.12 to 0.14 mm) while the lesser quality ones produced spacing factors from 0.007 to 0.008 (0.17 to 0.21 mm). He reports that several admixture marketing firms offer two AEA's, one fitting into each of the two categories.

Purpose

5. A research program was initiated to determine if some of the AEA's mentioned by Professor Geymayer and Mr. McCurrich, as well as some new American products, could produce an air-void system that would provide adequate frost protection with less than 9-percent air content in the mortar.

Scope

6. Concrete was made using neutralized vinsol resin (NVR) as the reference admixture and various other AEA's. The concretes were proportioned to meet the requirements of American Society for Testing and Materials (ASTM) C 233, "Standard Test Method for Air-Entraining Admixtures for Concrete" (ASTM 1989), except that the air content was specified as 2.5, 3.5, and 6.0 percent, ± 0.5 percent, for the low, medium, and high air contents,

respectively, and the slump requirement was 2-1/2 in. ± 1/2 in. (64 mm ± 13 mm). As the air content increased, less water was required to meet the slump requirement due to the workability imparted by the entrained air. Since the cement content remained constant, the water-cement ratios (w/c) ranged from 0.50 for the mixtures having low air content to approximately 0.44 for the mixtures having high air content. Tests of resistance to freezing-and-thawing were performed, and the spacing factors and specific surfaces were determined. Freezing-and-thawing tests were initiated after the concretes had attained a value of compressive strength of at least 3,500 psi (24.1 MPa). The AEA's were not tested for full compliance with ASTM C 260, "Standard Specification for Air-Entraining Admixtures for Concrete" (ASTM 1989), since this study was concerned only with the frost resistance of concrete at a selected air content.

PART II: EXPERIMENTAL PROGRAM

Materials

7. The following materials were used in the concrete mixtures:

- Type I portland cement (WESSC-12 C-1)
- Natural siliceous sand (WESSC-3 S-1)
- 3/4-in. (19.0-mm) nominal maximum size (NMS) crushed limestone coarse aggregate
- NVR (WESSC-12 AEA-2)
- AEA Brand A (CL-60 AEA-1041)
- AEA Brand B (CL-61 AEA-1044)
- AEA Brand C (WESSC-12 AEA-1)
- AEA Brand D (WESSC-3 AD-1)
- AEA Brand E (WESSC-3 AEA-1)

Test reports for these materials are given in Appendix A. The coarse aggregate was separated into individual sizes and recombined according to ASTM C 233, paragraph 4.2.2 (ASTM 1989). The test report for the coarse aggregate gives the results of tests of the recombined material. Attempts to obtain material from Fosroc Technology were unsuccessful. Brand B was material from Professor Geymayer. No tests were performed on the admixtures except for specific gravity and pH.

Concrete Mixtures

8. Typical mixture proportions for the low, medium, and high air contents are given in Table 1. At a higher air content, each of the AEA's provided water reduction beyond that of the NVR as evidenced by the lower water content and lower w/c. AEA Brand A provided more water reduction than did the others.

9. Concrete mixtures were also proportioned having a higher w/c for the AEA which provided the best frost protection. Since resistance to freezing and thawing might be reduced by the higher w/c, the AEA was tested only at

Table 1

Typical Mixture Proportions

Mixture	SSD Batch Weights, lb/yd³ (kg/m³)						
	Type I Portland Cement	Fine Aggregate	19.0-mm (3/4-in.) NMS Coarse Aggregate	Water	W/C	Air Content, %	Fine-Total Aggregate Ratio, %
Low air	521 (309)	1,275 (756)	2,015 (1,273)	260 (155)	0.500	2.5	40
Medium air	521 (309)	1,262 (749)	1,996 (1,184)	255 (151)	0.490	3.5	40
High air	521 (309)	1,234 (732)	1,950 (1,157)	232 (138)*	0.446**	6.5	40

* 228 (135) for AEA Brand A, 235 (139) for NVR.

** 0.438 for AEA Brand A, 0.451 for NVR.

medium and high air contents. These mixtures had a cement content less than that specified in ASTM C 233 (ASTM 1989), but the slump was maintained at 2-1/2 in. ± 1/2 in. (64 mm ± 13 mm). The mixture proportions are given in Table 2.

Test Procedures

10. Three duplicate batches of concrete were made representing each air content and each AEA. Each of the standards cited in this paragraph are found in the 1989 Annual Book of ASTM Standards (ASTM 1989). The slump (ASTM C 143-89a), air content (ASTM C 231-89a), and unit weight (ASTM C 138-81) were measured on the fresh concrete. Two 6-in.-diam by 12-in.-high (154- by 305-mm) cylindrical specimens were cast (ASTM C 192-88) from each batch of concrete for compressive strength testing (ASTM C 39-86) at 14 and 28 days age. Two 3-1/2- by 4-1/2- by 16-in. (89-mm by 114-mm by 406-mm) prisms were cast (ASTM C 192-88) from each batch of concrete for rapid freezing-and-thawing testing (ASTM C 666-84). Air content, spacing factor, and specific surface of the air-void system in the hardened concrete was determined (ASTM C 457-82a) from prisms representing most of the AEA's and the air contents. A total of 138 cylinders and 138 prisms were cast and tested representing 69 batches of concrete. A summary of the test groups in this investigation is given in Table 3.

Table 2

Mixture Proportions with High Water-Cement Ratio

	SSD Batch Weights, lb/yd^3 (kg/m^3)						
Mixture	Type I Portland Cement	Fine Aggregate	19.0-mm (3/4 in.) NMS Coarse Aggregate	Water	W/C	Air Content, %	Fine-Total Aggregate Ratio, %
Medium air	415 (246)	1,347 (799)	2,098 (1,245)	270 (160)	0.650	3.5	42
High air	415 (246)	1,319 (783)	1,919 (1,138)	245 (145)	0.590	6.5	42

Table 3

Test Matrix

AEA	Air Content	No. of Batches
NVR	Low (L)	3
NVR	Medium (M)	3
NVR	High (H)	3
A	L	6
A	M	6
A	H	3
B	L	3
B	M	3
B	H	3
C	L	3
C	M	3
C	H	3
D	L	3
D	M	3
D	H	3
E	L	3
E	M	3
E	H	3
CON*	L	3
A**	M	3
A**	H	3

* No AEA was used.
** High w/c.

PART III: TEST RESULTS AND DISCUSSION

Test Results

11. The cylindrical specimens were tested for compressive strength (ASTM C 39) (ASTM 1989) at 14 and 28 days age. All mixtures had compressive strengths greater than 3,500 psi at 14 days age. Tests for resistance to freezing and thawing were initiated on the prisms at 14 days age in accordance with ASTM C 666, Procedure A (ASTM 1989). The nominal freezing-and-thawing cycle of lowering the temperature from 40 to 0 °F (4.4 to -17.8 °C) and raising it from 0 to 40 °F (-17.8 to 4.4 °C) required 2 hr. The relative dynamic modulus was measured at regular intervals. Testing was continued until one of the following conditions occurred: (a) the relative dynamic modulus of elasticity (Relative E) reached 60 percent, or (b) 300 freezing-and-thawing cycles were accomplished. The durability factor was calculated after completion of the test. Plots of relative dynamic modulus of elasticity versus number of freezing-and-thawing cycles for each concrete are given in Appendix B.

12. Tests for determination of air content and spacing factors of hardened concrete were conducted on representative beams from each group in accordance with ASTM 457 (ASTM 1989). All test results are given in Table 4.

Discussion

General

13. The criterion used by the Corps of Engineers for acceptability of an AEA is found in ASTM C 260 (ASTM 1989). The AEA must be capable of producing an air-void system that will render the paste in the concrete adequately resistant to freezing and thawing. This criterion requires that the relative durability factor of the concrete containing the admixture under test shall be not less than 80; that is, the durability factor of concrete made with the admixture under test shall be at least 80 percent of the durability factor of concrete made with the reference admixture. The reference concrete is that made with NVR and having the high air content.

Table 4

Test Results*

Brand AEA	Specified Air Content	w/c	No. of Batches	Average Slump, in.	Average Unit Weight lb/ft^3	Average Air Content %	Average Mortar Air Content %	Avg. Compressive Strength psi 14 day	Avg. Compressive Strength psi 28 day	Durability Factor (DF)	Relative Durability Factor**	Point Count Air Content %	Spacing Factor in.	Specific Surface $in.^2/in.^3$
NVR	L	0.500	3	2-3/4	152.0	2.3	4.1	4,460	†	7	8	2.5	0.0156	392
NVR	M	0.490	3	3	149.2	3.4	6.0	4,090	†	52	58	3.1	0.0099	559
NVR	H	0.451	3	3	146.1	6.2	10.8	3,790	†	90	100**	6.2	0.0056	685
A	L	0.500	6	2-3/4	150.6	2.5	4.4	4,570	5,370	22	24	3.0	0.0126	442
A	M	0.490	6	3	149.0	3.6	6.4	4,620	5,130	76	84	5.4	0.0067	888
A	H	0.438	3	2-1/2	146.5	6.1	10.6	3,730	4,170	91	101	5.0	0.0045	1,011
B	L	0.500	3	2-1/4	151.3	2.3	4.1	4,910	5,540	6	7	3.0	0.0148	366
B	M	0.490	3	3	149.5	3.2	5.6	4,850	5,080	54	60	3.0	0.0118	466
B	H	0.446	3	2-3/4	146.0	6.3	10.9	4,200	4,600	90	100	4.4	0.0047	950
C	L	0.500	3	2-1/2	151.3	2.2	3.8	5,040	5,670	5	6	†	†	†
C	M	0.490	3	3	150.1	3.2	5.7	4,710	5,240	32	36	3.2	0.0121	414
C	H	0.446	3	2-1/4	146.7	6.1	10.5	4,610	4,760	71	79	5.8	0.0060	591
D	L	0.500	2	3-1/4	151.2	2.3	4.2	4,820	5,410	6	7	†	†	†
D	M	0.490	4	2-3/4	150.1	3.3	5.8	4,570	5,160	35	39	2.4	0.0096	621
D	H	0.446	3	2-3/4	146.0	6.5	11.2	4,280	4,640	89	99	†	†	†
E	L	0.500	3	2-3/4	149.9	2.5	4.4	5,140	5,650	16	18	3.4	0.0158	337
E	M	0.490	3	2-1/2	148.7	3.6	6.3	4,780	3,290	69	77	3.7	0.0093	559
E	H	0.446	3	2-1/2	145.2	6.7	11.5	4,090	4,710	83	92	5.9	0.0060	937
None	L	0.505	3	2	151.2	1.7	3.1	5,310	5,630	2	2	†	†	†
A††	M	0.650	3	3	148.5	3.4	5.9	3,510	4,110	37	41	3.3	0.0112	444
A††	H	0.590	3	3	143.7	6.4	10.9	3,200	3,740	85	94	8.0	0.0042	641

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

** NVR is the reference admixture referred to in ASTM C 233 (ASTM 1989); the NVR Concrete with 6 percent air is the reference concrete, see ASTM C 260 (ASTM 1989).

† Test not run.

†† High w/c.

14. ACI 211.1 (ACI 1991) recommends, in Table 6.3.3, the air content for various nominal maximum size aggregates (NMSA) and different exposure conditions. Total air contents of 3.0, 4.5, and 6.0 percent are recommended for mild, moderate, and severe exposure, respectively, for 1-in. (25.0 mm) NMSA. This translates to approximately 5.0, 8.0, and 10.0 percent air in the mortar. A plot of mortar air content versus durability factor (Figure 1) shows that there can be a significant difference in the durability factor at the same air content when different AEA's are used.

Low air content

15. The range of air contents comprising this group was from 2.2 to 2.5 percent (1.7 percent for no AEA). Mortar air contents ranged from 3.8 to 4.4 percent (3.1 percent for no AEA). Upon review of the relative durability factors, which ranged from 6 to 24 (2 for no AEA), it can be concluded that none of the concretes made with these low air contents satisfied the criterion for providing acceptable frost resistance. Spacing factors for concretes in this group ranged from 0.0126 to 0.0158 in. (0.32 to 0.40 mm). These values exceed the recommended minimum criterion for frost durability, 0.008 in. (0.20 mm).

Medium air content

16. The range of air contents in this group was from 3.2 to 3.6 percent. Mortar air contents ranged from 5.6 to 6.4 percent. A review of the relative durability factors indicates that only Brand A provided adequate frost protection for severe exposures with a relative durability factor of 84. Only Brand A produced a spacing factor (0.0067 in. (0.17 mm)) within the recommended criterion.

High air content

17. The range of air contents in this group was from 6.1 to 6.7 percent. Mortar air contents ranged from 10.5 to 11.5 percent. All AEA's except Brand C produced satisfaction relative durability factors. Spacing factors for concretes in this group ranged from 0.0045 to 0.0060 in. (0.011 to 0.015 mm), all of which are within recommended criterion.

High water-cement ratio

18. While Brand A provided adequate frost protection at medium and high air contents when the concretes had w/c below 0.50, such was not the case with higher w/c. At a w/c of 0.65, the relative durability factor was only 41 for

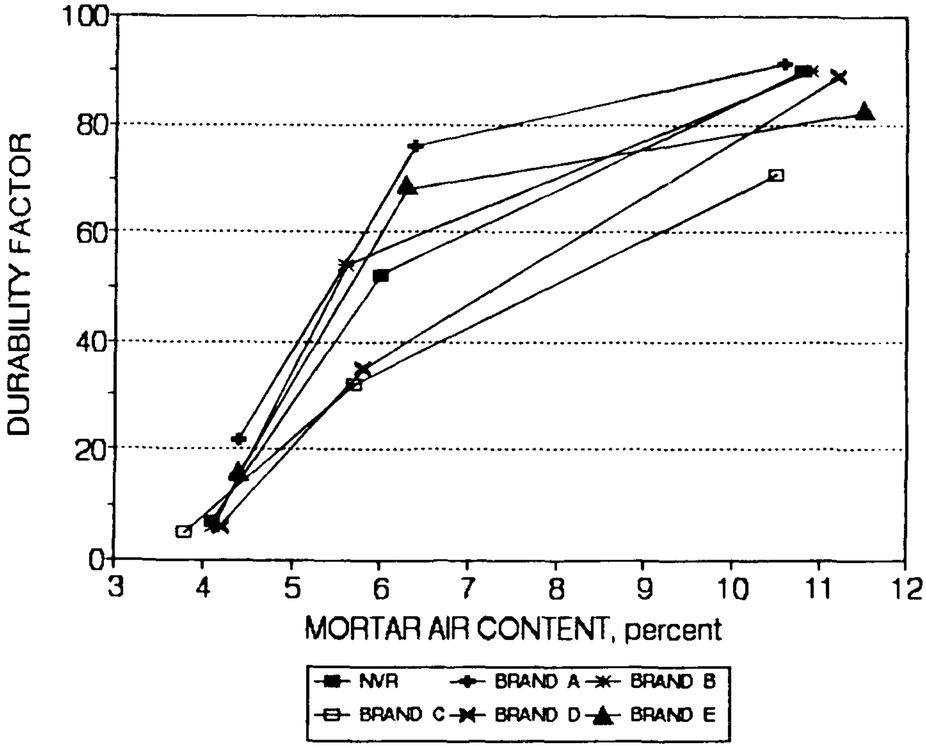

Figure 1. Mortar air content versus durability factor

the concrete having medium air content. Concretes with a w/c of 0.59 and high air content had a relative durability factor of 94. Therefore, it would appear that high air content is necessary when concretes have w/c above 0.50, even when AEA's are used that give smaller air voids.

Point-count air contents

19. All AEA's appeared to produce bubbles which remained stable during fabrication of test specimens and through time of final setting. In general, the air content measured in the hardened concrete exceeded 80 percent of those measured in the fresh concrete.

Spacing factor and specific surface

20. It is obvious from the results presented above that some differences exist in the performance of various AEA's. A review of the spacing factors and specific surfaces reveals some factors that might explain why Brand A provided better frost protection.

21. The data indicate that the durability factor is linearly related, with good correlation coefficients, to both spacing factor and specific

surface, as shown in Figures 2 and 3, respectively. The spacing factor also appears to be linearly related to specific surface (Figure 4). These data indicate that for concrete having a given durability factor, Brand A produces an air-void system having both a smaller spacing factor and a higher specific surface than any of the other AEA's. It is significant that these smaller spacing factors and higher specific surfaces were produced at lower air contents. A plot of mortar air content versus spacing factor (Figure 5) indicates that when NVR, Brand B and Brand E were used, an additional 1 to 2 percent air in the mortar was necessary to produce a spacing factor equivalent to that produced by Brand A. Spacing factors were generally 20 to 30 percent smaller for Brand A than for NVR, with the greatest advantage being at the medium air content. The data also indicate that a spacing factor of 0.008 in. (0.2 mm) was achieved with a mortar air content of less than 9 percent.

22. The data presented in Figure 4 indicate that the specific surface was approximately 100 sq in./cu in. higher for Brands A, B, and E than for NVR at a spacing factor of 0.008 in. A plot of mortar air content versus specific surface (Figure 6) indicates that when NVR, Brand B, and Brand E were used, the specific surfaces were from 200 to 400 sq in./cu in. less than those produced with Brand A when the mortar air contents were between 5 and 11 percent. The most notable increases were at the medium and high air contents where the specific surfaces were 60 and 50 percent greater than those produced by the NVR. In fact, it appears from the data presented in Figure 6 that within the range of normal air content, the other AEA's may never produce specific surfaces as high as Brand A.

23. There was good correlation, using the equation

$$Y = A\ (\log (X))^2 + B \log (X) + C$$

between mortar air content and both spacing factor and specific surface (Figures 5 and 6). Using the equations of these lines, as well as those in Figures 2 and 3, equations were formed which predict the durability factor for a known mortar air content. Equations were formed using both spacing factor and specific surface data. Each equation gives similar results. Taking Brand A as an example, Equation 1, using the spacing factor data, predicts a durability factor of 93 with a mortar air content of 9.0 percent. Equation 2,

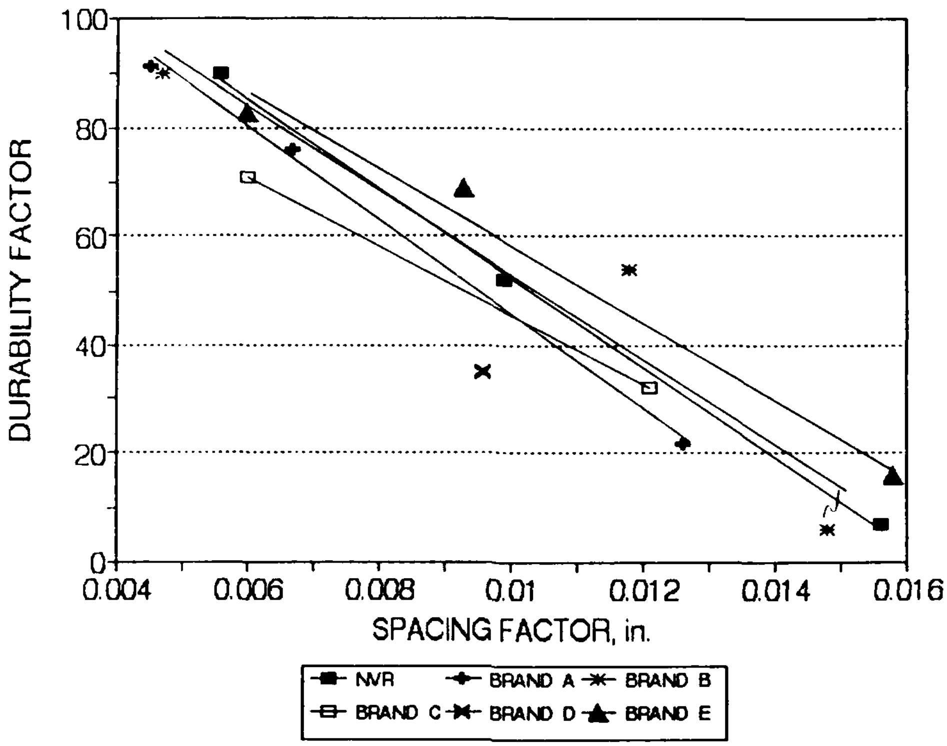

Figure 2. Spacing factor versus durability factor

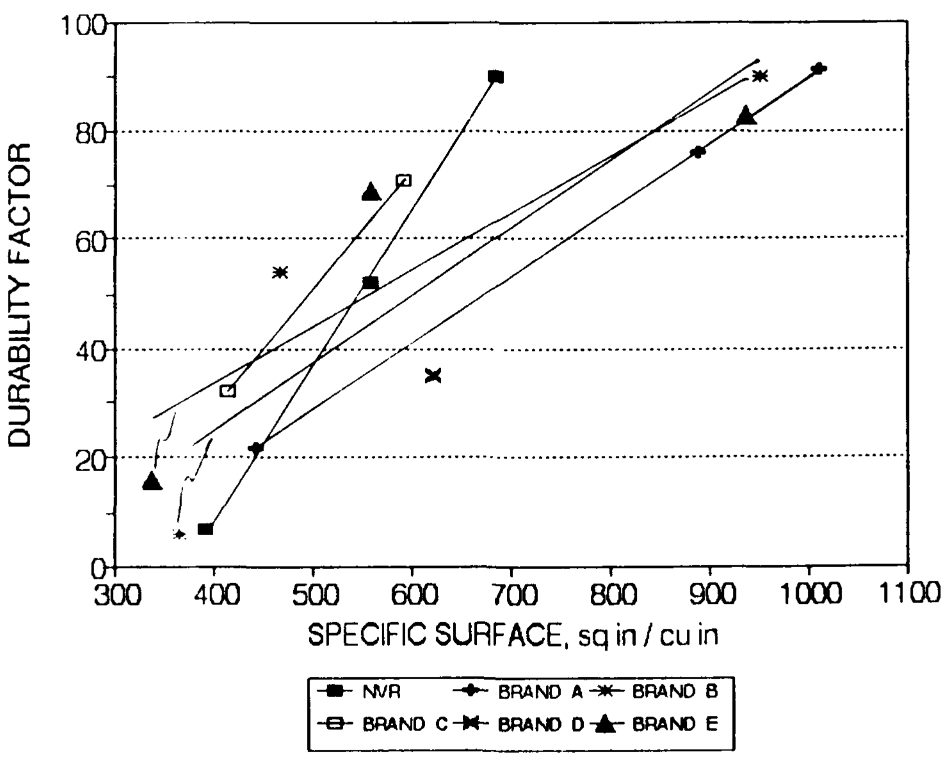

Figure 3. Specific surface versus durability factor

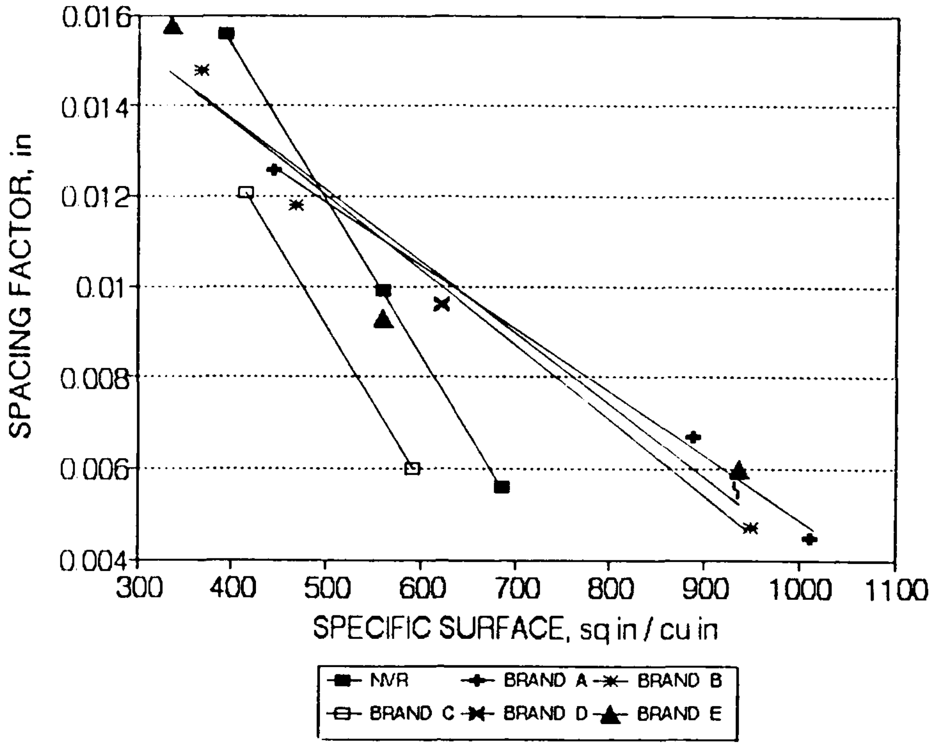

Figure 4. Specific surface versus spacing factor

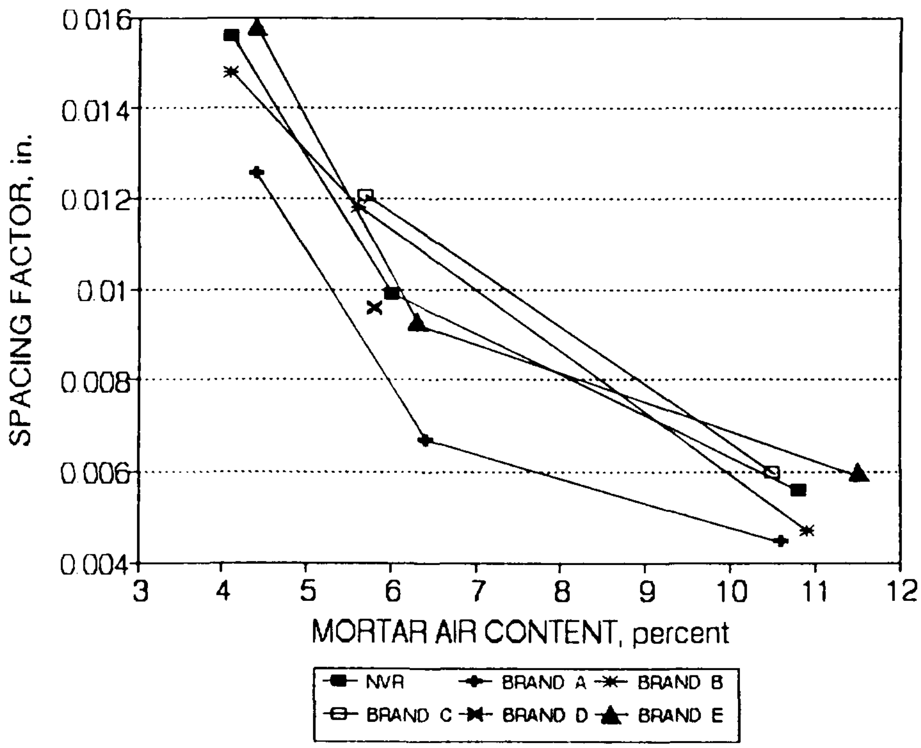

Figure 5. Mortar air content versus spacing factor

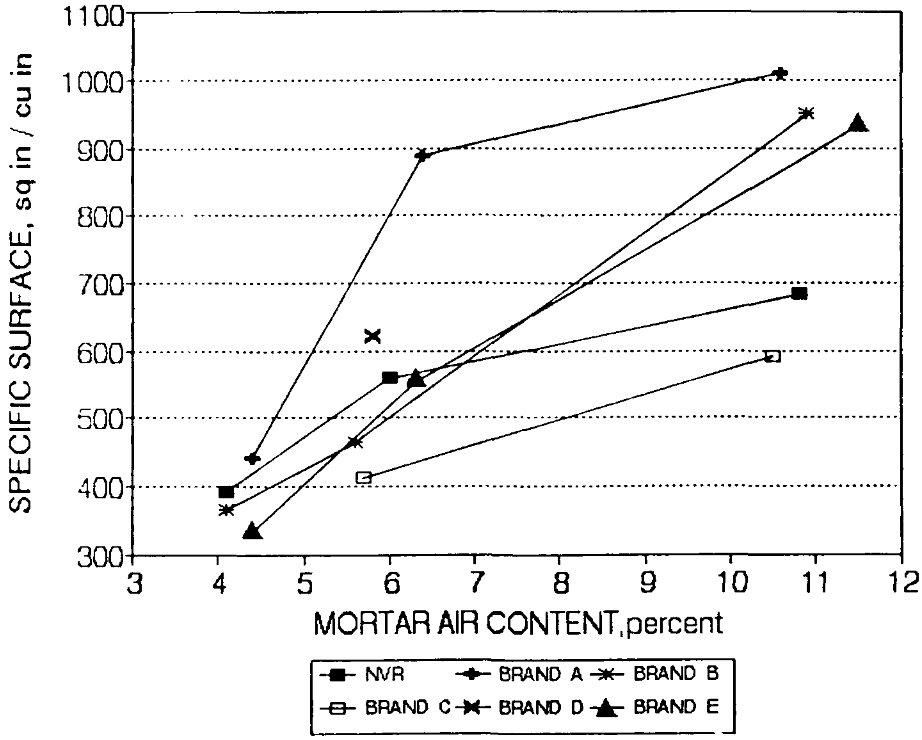

Figure 6. Mortar air content versus specific factor

using the specific surface data, also predicts a durability factor of 93 with a mortar air content of 9.0 percent. A review of the plot of mortar air contents versus durability factors (Figure 1) shows that both predictions are highly accurate. The equations for each AEA tested are given in Appendix C.

$$DF = -593\ (\log(MA))^2 + 1173\ \log(MA) - 486 \tag{1}$$

where

DF = durability factor

MA = mortar air content

$$DF = -691\ (\log(MA))^2 + 1333\ \log(MA) - 550 \tag{2}$$

While there may be little significance in the exact form of these equations, it is significant that a very good correlation exists. It provides further evidence of the relationship between air content and frost resistance and that spacing factor and specific surface are the controlling parameters.

Summary

24. From the test results obtained in this investigation, it appears that frost-resistant concrete can be produced with mortar air content as low as 6.0 percent using some AEA's. Brand A provided satisfactory frost resistance at the medium air content. All AEA's provided adequate frost protection at high air content except Brand C. The satisfactory performance associated with Brand A at a reduced air content appears to result from smaller spacing factors and higher specific surfaces. At equivalent air content, Brand A appears to generate an air-void system comprised of smaller voids that are necessarily closer together.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

25. There can be a significant difference in the frost resistance of a concrete at the same air content when different AEA's are used. All but one of the AEA's tested provided adequate frost resistance at high air content (greater than 9 percent in the mortar). However, only one, Brand A, provided adequate frost resistance for severe exposure at the medium air content (5.6 to 6.4 percent in the mortar). When the w/c exceeded 0.50, Brand A provided satisfactory frost resistance at the high air content.

26. The superior frost resistance provided by Brand A appears to result from smaller spacing factors and higher specific surfaces at lower air contents than are present with the other AEA's. At equivalent air content, Brand A generates an air-void system comprised of smaller voids that are spaced closer together. Simply because a product claims to be an AEA, one should never assume that it will generate a proper air-void system. All AEA's should be tested for compliance with ASTM C 260 (ASTM 1989) prior to their approval for use, with particular attention to the requirement that, in the test for resistance to freezing and thawing, the relative durability factor be not less than 80.

27. If a high quality AEA such as Brand A is used, it should be acceptable to specify a minimum mortar air content of 6.0 percent. This translates to a total concrete air content of approximately 3.5 percent for 1-in. (25.0-mm) NMSA. This air content is lower than that currently recommended by ACI 211.1 (ACI 1991). However, prior to approval of such, the AEA in question should be tested according to ASTM C 233 (ASTM 1989) and shown to provide adequate frost protection at those air contents. Unless an AEA has proven capable of providing adequate frost protection at lower air content, current recommendations given in ACI 211.1 should be used for specifying air content.

28. An AEA such as Brand A could be more effective than NVR at producing a proper air-void system when used in combination with a high-range water-reducing admixtures (HRWR). Since this AEA produces small spacing factors and high specific surfaces, it could help to overcome the tendencies

for concretes made with HRWR to have large spacing factors and low specific surfaces.

Recommendations

29. It is recommended that additional testing be conducted to confirm these findings. Other AEA's should be tested at the mortar air content used in this study and at mortar air content of approximately 8 to 9 percent. The relationship between spacing factor and specific surface for AEA's such as Brand A should be further developed. The AEA's should also be evaluated when used in combination with HRWR.

30. Lower air content could be considered for concretes having w/c not exceeding 0.50 if the AEA has been tested and shown to provide adequate frost protection at those lower air content.

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APPENDIX A: MATERIALS TEST REPORTS

REPORT OF TESTS ON HYDRAULIC CEMENT

TO:

Steve Ragan/Billy Neeley
Structures Laboratory

FROM:
U. S. Army Corps of Engineers
Waterways Experiment Station
Cement and Pozzolan Unit
3909 Halls Ferry Road
Vicksburg, Mississippi 39180-6199

Company: Lone Star Industries
Location: Cape Girardeau, MO
Specification: ASTM C 150,I/II
Contract No.:
Project: Low-Air Durable Concrete

Test Report No.: WES-172-89
Program: Single Sample
CTD No.: WESSC-12, C-1
Job No.: QG9S121S1170001
Date Sampled: 16 August 1989

________Partial test result

9/11/89 Tests complete, material X does, ____ does not meet specification

	Result	Retest	Spec Limits (Type I/II)
Chemical Analysis			
SiO_2, %	21.6		20.0 min
Al_2O_3, %	4.2		6.0 max
Fe_2O_3, %	3.0		6.0 max
CaO, %	63.4		-
MgO, %	3.2		6.0 max
SO_3, %	2.8		3.0 max
Loss on ignition, %	1.0		3.0 max
Insoluble residue, %	0.12		0.75 max
Na_2O, %	0.10		-
K_2O, %	0.71		-
Alkalies-total as Na_2O,%	0.57		0.60 max
TiO_2, %	0.13		-
P_2O_5, %	0.04		-
C_3A, %	7		8 max
C_3S, %	52		-
C_2S, %	23		-
C_4AF, %	9		-
Physical Tests			
Heat of hydration, 7-day, cal/g	-		70 max
Surface area, m^2/kg (air permeability)	370		280 min
Autoclave expansion, %	0.05		0.80 max
Initial set, min. (Gillmore)	155		60 min
Final set, min. (Gillmore)	250		600 max
Air content, %	10		12 max
Compressive strength, 3-day, psi	3160		1800 min
Compressive strength, 7-day, psi	4020		2800 min
False set (final penetration), %	-		50 min

REMARKS:

CF:

Toy S. Poole

Toy S. Poole
Chief, Cement and Pozzolan Group

Information given in the report shall not be used in advertising or sales promotion to indicate endorsement of this product by the U.S. Government.

Fine Aggregate Test Report

Sieve Size	Cumulative Percent Passing
4.75-mm (No. 4)	100
2.36-mm (No. 8)	89
1.18-mm (No. 16)	71
600-μm (No. 30)	52
300-μm (No. 50)	15
150-μm (No. 100)	3
75-μm (No. 200)	1

Specific gravity: 2.62

Absorption: 1.10 %

Type: Natural siliceous sand

Coarse Aggregate Test Report

Sieve Size	Cumulative Percent Passing
25.0-mm (1 in.)	100
19.0-mm (3/4 in.)	75
12.5-mm (1/2 in.)	50
9.5-mm (3/8-in.)	25
4.75-mm (No. 4)	0

Specific gravity: 2.76

Absorption: 0.50 %

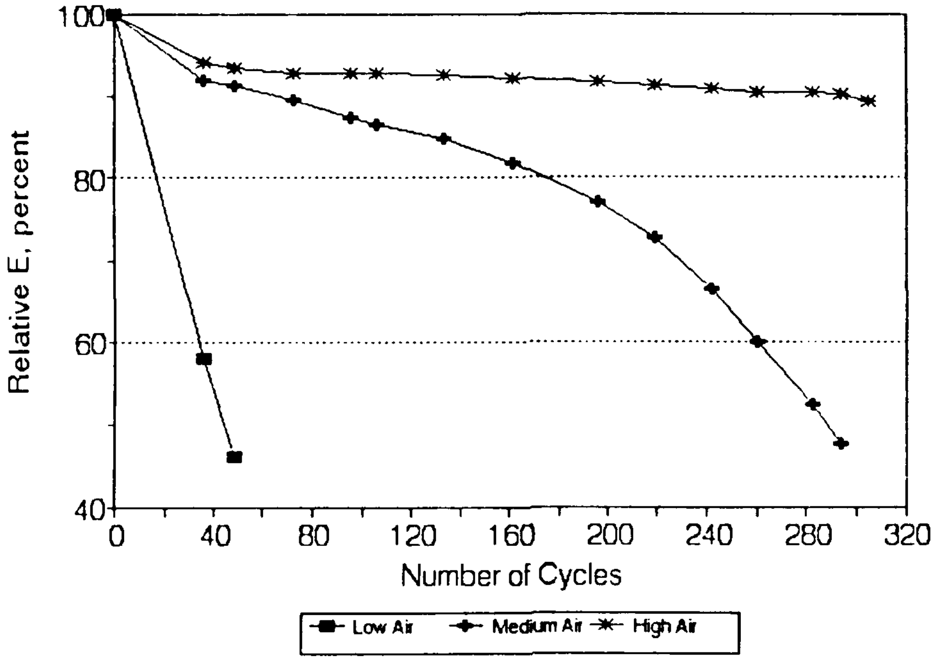
Type: Crushed limestone

AEA Test Results

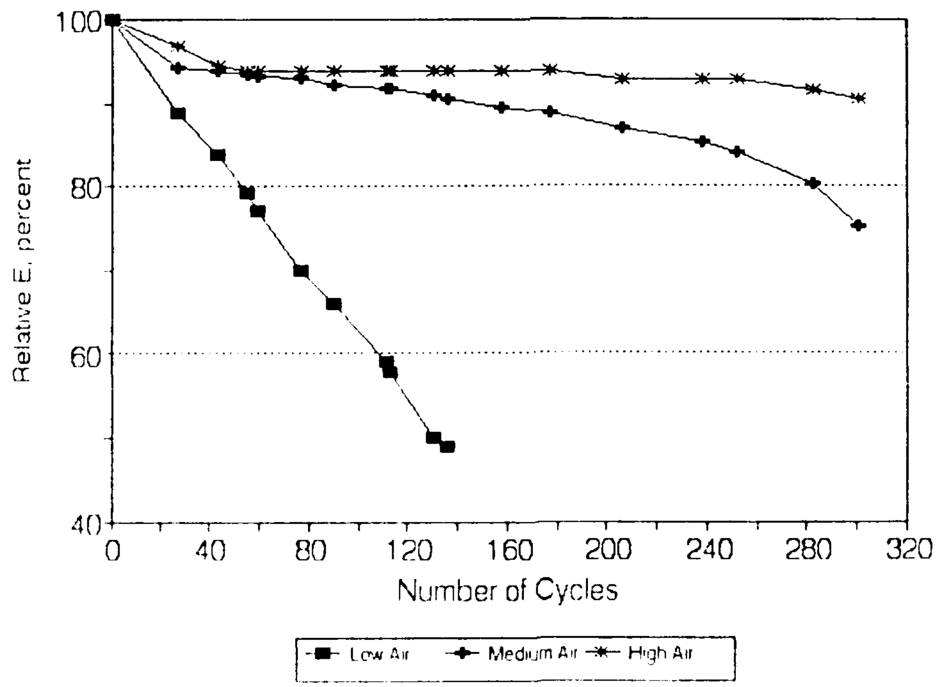
AEA	Specific Gravity	pH %
A	1.010	10.25
B	1.030	9.44
C	1.005	9.01
D	1.012	9.19
E	1.023	8.04
NVR	1.025	10.32

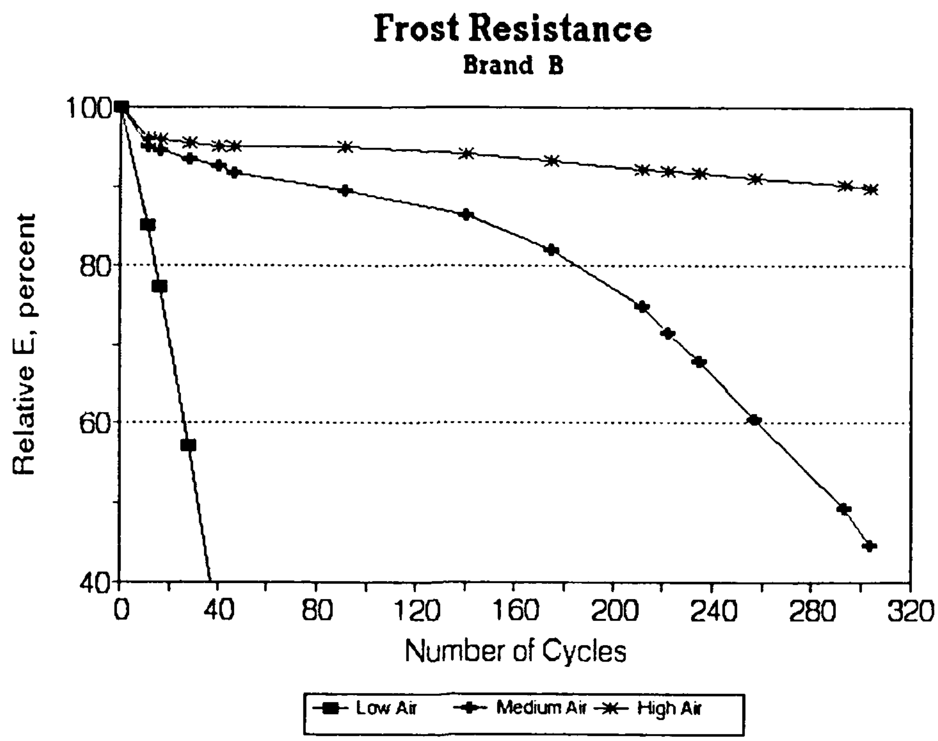
APPENDIX B: PLOTS OF RELATIVE DYNAMIC MODULUS OF ELASTICITY VERSUS NUMBER OF FREEZING-AND-THAWING CYCLES

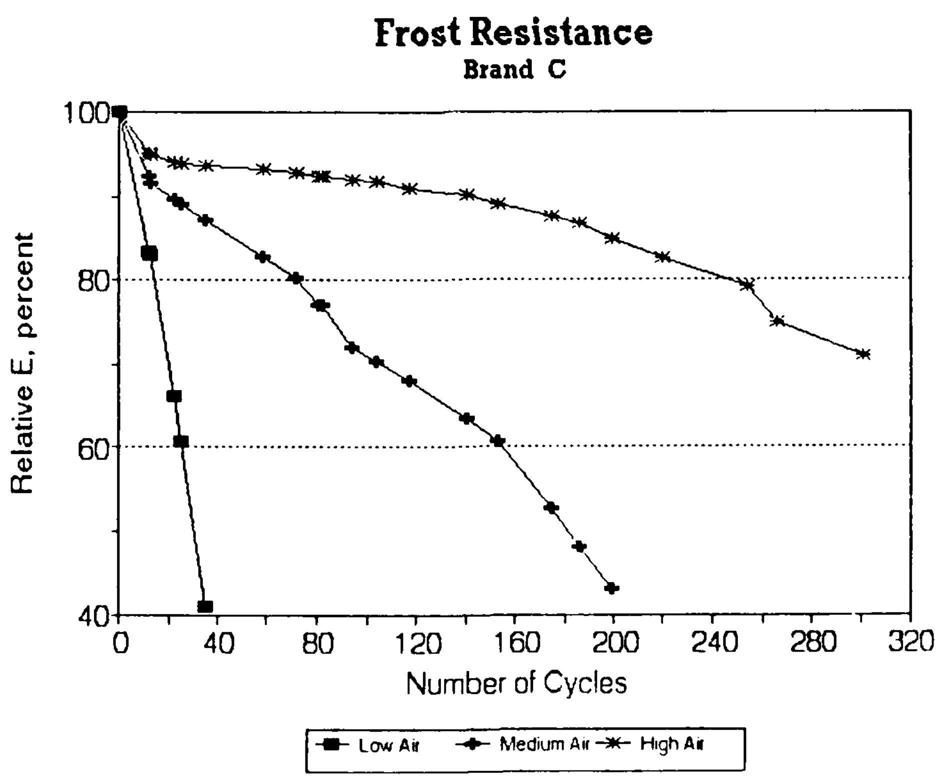
Frost Resistance
Neutralized Vinsol Resin



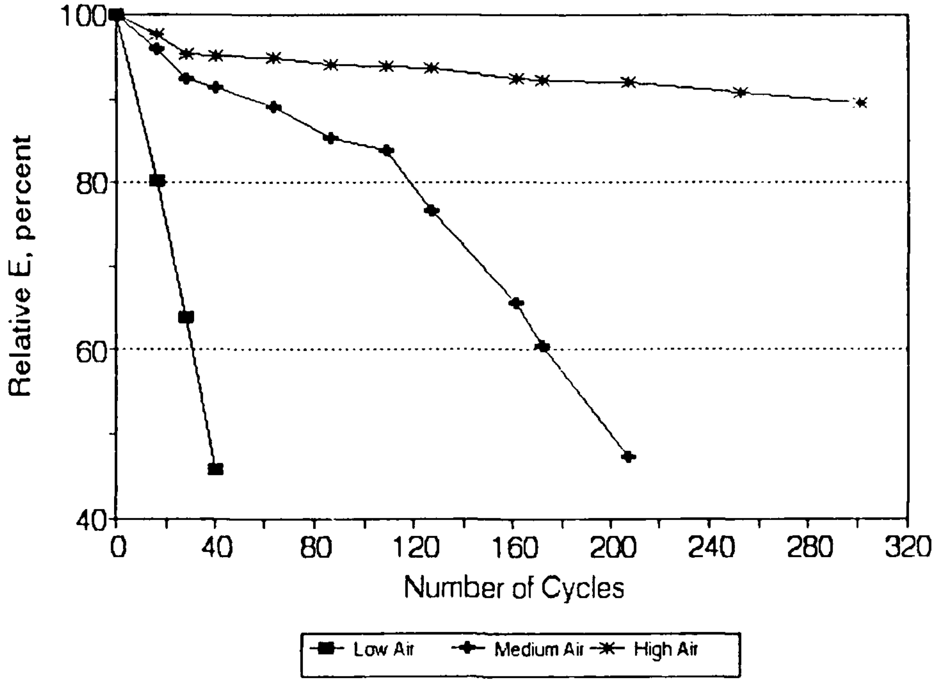
Frost Resistance
Brand A



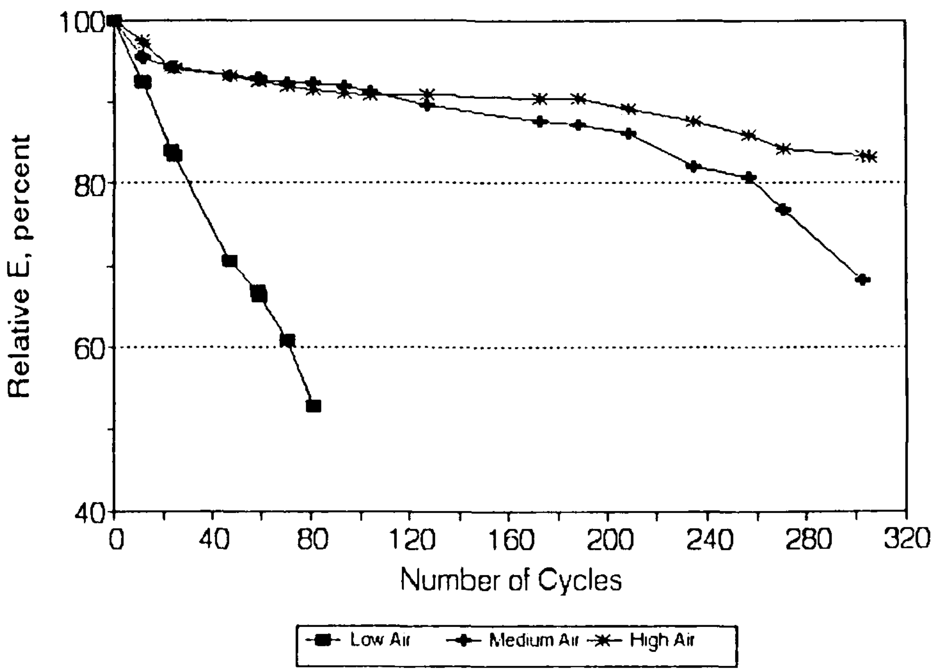

Frost Resistance
Brand B
100
80
60
40
Relative E, percent
0
40
80
120
160
200
240
280
320
Number of Cycles
Low Air
Medium Air
High Air


Frost Resistance
Brand C
100
80
60
40
Relative E, percent
0
40
80
120
160
200
240
280
320
Number of Cycles
Low Air
Medium Air
High Air

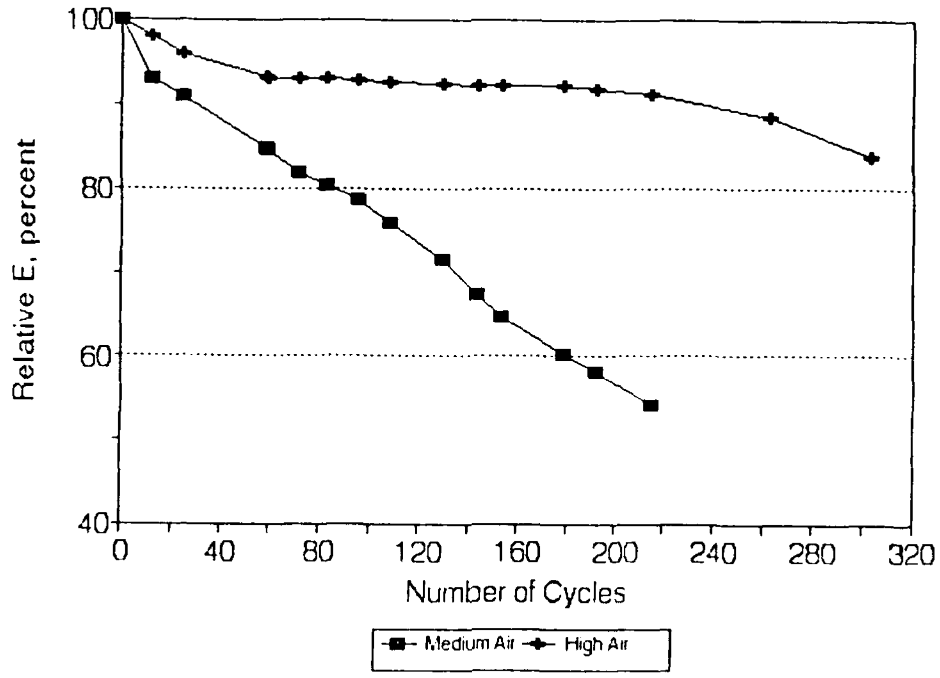
Frost Resistance
Brand D



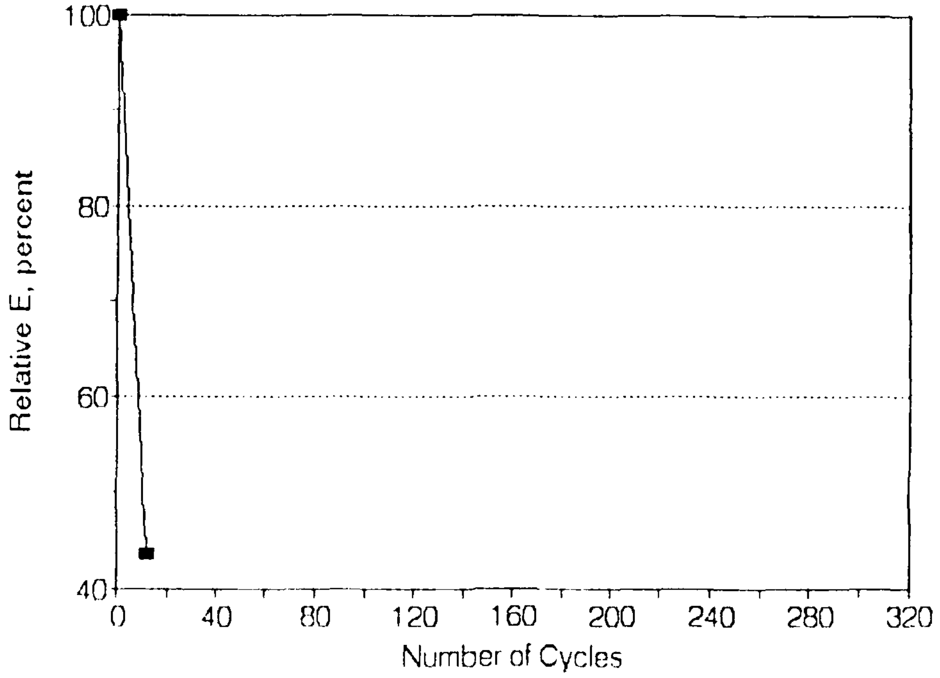
Frost Resistance
Brand E



Frost Resistance
Brand A (High W/C)



Frost Resistance
No AEA



APPENDIX C:
EQUATIONS TO ESTIMATE DURABILITY FACTOR

NVR

<u>Spacing Factor</u>

$$DF = -8307\ \bar{L} + 136$$

correlation coefficient = -0.999

$$\bar{L} = 0.0567 - 0.0927 \log(MA) + 0.0419 (\log(MA))^2$$

nonlinear correlation = 1.000

where: DF = durability factor

$\bar{L}$ = spacing factor

MA = mortar air content

$$DF = -348 (\log(MA))^2 + 770 \log(MA) - 335$$

Mortar Air Content, %	Predicted DF	Actual DF
4.1	6	6.8
6.0	53	51.8
10.8	89	90.1

NVR

Specific Surface

$$DF = 0.284\,\alpha - 105$$

correlation coefficient = -0.999

$$\alpha = -812 + 2717 \log(MA) - 1227 (\log(MA))^2$$

nonlinear correlation = 1.000

where: DF = durability factor

α = specific surface

MA = mortar air content

$$DF = -348 (\log(MA))^2 + 772 \log(MA) - 335$$

Mortar Air Content, %	Predicted DF	Actual DF
4.1	6	6.8
6.0	55	51.8
10.8	91	90.1

Brand A

<u>Spacing Factor</u>

$$DF = -8027\ \bar{L} + 131$$

correlation coefficient = -0.998

$$\bar{L} = 0.0715 - 0.136 \log (MA) + 0.0687 (\log (MA))^2$$

nonlinear correlation = 1.000

where: DF = durability factor

$\bar{L}$ = spacing factor

MA = mortar air content

$$DF = -593 (\log (MA))^2 + 1173 \log (MA) - 486$$

Mortar Air Content, %	Predicted DF	Actual DF
4.4	23	21.9
6.4	74	75.8
10.6	93	90.7

Brand A

Specific Surface

$$DF = 0.121\ \alpha - 32$$

correlation coefficient = 1.000

$$\alpha = -4280 + 11014 \log(MA) - 5708 (\log(MA))^2$$

nonlinear correlation = 1.000

where: DF = durability factor

α = specific surface

MA = mortar air content

$$DF = -691 (\log(MA))^2 + 1333 \log(MA) - 550$$

Mortar Air Content, %	Predicted DF	Actual DF
4.4	22	21.9
6.4	76	75.8
10.6	90	90.7

Brand B

Spacing Factor

$$DF = -7742\ \bar{L} + 130$$

correlation coefficient = -0.952

$$\bar{L} = 0.0258 - 0.0145 \log (MA) - 0.0056 (\log (MA))^2$$

nonlinear correlation = 1.000

where: DF = durability factor

$\bar{L}$ = spacing factor

MA = mortar air content

$$DF = 43 (\log (MA))^2 + 112 \log (MA) - 70$$

Mortar Air Content, %	Predicted DF	Actual DF
4.1	15	5.5
5.6	38	53.5
10.9	92	89.6

Brand B

Specific Surface

$$DF = 0.122\,\alpha - 23$$

correlation coefficient = -0.903

$$\alpha = 923 - 2258 \log(MA) + 2201 (\log(MA))^2$$

nonlinear correlation = 1.000

where: DF = durability factor

α = specific surface

MA = mortar air content

$$DF = 269 (\log(MA))^2 - 275 \log(MA) + 90$$

Mortar Air Content, %	Predicted DF	Actual DF
4.1	22	5.5
5.6	35	53.5
10.9	94	89.6

Brand C

Spacing Factor

$$DF = -6426 \bar{L} + 110$$

correlation coefficient = -1.000 (only 2 data points)

$$\bar{L} = 0.0171 + 0.0054 \log (MA) - 0.0160 (\log (MA))^2$$

nonlinear correlation = 1.000 (only 2 data points)

where: DF = durability factor

$\bar{L}$ = spacing factor

MA = mortar air content

$$DF = 103 (\log (MA))^2 - 35 \log (MA)$$

Mortar Air Content, %	Predicted DF	Actual DF
3.8	14	5.2
5.7	32	32.1
10.5	72	71.3

Brand C

Specific Surface

$DF = 0.221\ \alpha - 60$

correlation coefficient = 1.000 (only 2 data points)

$\alpha = 45 + 353 \log (MA) + 177 (\log (MA))^2$

nonlinear correlation = 1.000

where: DF = durability factor

α = specific surface

MA = mortar air content

$DF = 39 (\log (MA))^2 + 78 \log (MA) - 50$

Mortar Air Content, %	Predicted DF	Actual DF
3.8	0	5.2
5.7	31	32.1
10.5	70	71.3

Brand E

Spacing Factor

$$DF = -7071\ \bar{L} + 129$$

correlation coefficient = -0.991

$$\bar{L} = 0.0785 - 0.1422 \log(MA) + 0.0697 (\log(MA))^2$$

nonlinear correlation = 1.000

where: DF = durability factor

$\bar{L}$ = spacing factor

MA = mortar air content

$$DF = -493 (\log(MA))^2 + 1005 \log(MA) - 426$$

Mortar Air Content, %	Predicted DF	Actual DF
4.4	17	15.7
6.3	62	69.0
11.5	85	83.2

Brand E

Specific Surface

$$DF = 0.104\ \alpha - 8$$

correlation coefficient = 0.891

$$\alpha = -552 + 1347 \log (MA) + 53 (\log (MA))^2$$

nonlinear correlation = 1.000

where: DF = durability factor

α = specific surface

MA = mortar air content

$$DF = 6 (\log (MA))^2 + 140 \log (MA) - 65$$

Mortar Air Content, %	Predicted DF	Actual DF
4.4	28	15.7
6.3	51	69.0
11.5	90	83.2

Brand A (High W/C)

Spacing Factor

$DF = -6786 \bar{L} + 113$

correlation coefficient = -1.000 (only 2 data points)

$\bar{L} = 0.36 - 0.77 \log (MA) + 0.411 (\log (MA))^2$

nonlinear correlation = 1.000 (only 2 data points)

where: DF = durability factor

$\bar{L}$ = spacing factor

MA = mortar air content

$DF = -2789 (\log (MA))^2 + 5225 \log (MA) - 2330$

Mortar Air Content, %	Predicted DF	Actual DF
5.9	40	37.3
10.9	89	84.8

Brand A (High W/C)

Specific Surface

$DF = 0.241\ \alpha - 70$

correlation coefficient = 1.000 (only 2 data points)

$\alpha = 15900 + 35500 \log(MA) + 2.0100 (\log(MA))^2$

nonlinear correlation = 1.000 (only 2 data points)

where: DF = durability factor

α = specific surface

MA = mortar air content

$DF = 4844 (\log(MA))^2 - 8556 \log(MA) + 3762$

Mortar Air Content, %	Predicted DF	Actual DF
5.9	45	37.3
10.9	99	84.8